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CHALCOGENIDE As_2Se_3 MULTI CLADDING MICROSTRUCTURED OPTICAL FIBER WITH HIGH NONLINEARITY AND FLATTENED DISPERSION IN MID-INFRARED RANGE

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Abstract- In this paper a new design of multi-cladding micro-structured optical fiber (MC-MOF) with As_2Se_3 chalcogenide core and air-holed cladding is proposed. Calculations of nonlinear coefficient, confinement loss, effective area and dispersion are performed by employing plane wave expansion method. By using 10 hexagonal rings consisting of air holes with different diameters in the cladding, a low dispersion of about 5 ps/nm/km at wavelength of 1.55 µm, and a flattened dispersion by -5 ps/nm/km over the wavelength range of 8.8 to 18 µm with a high nonlinear coefficient and low confinement loss can be achieved. In this design, the nonlinearity coefficient γ at 11 to 18 µm wavelength range is as high as 1 $W^{-1}m^{-1}$ and the confinement loss at the wavelength range less than 13 µm is around zero. This structure can be used in applications such as broadband optical amplification, wavelength conversion and super-continuum generation in mid-infrared region.

Keywords: Chalcogenide Glass, Multi-Cladding Microstructure Optical Fiber, Flattened Dispersion, Confinement Loss, Effective Area, Nonlinear Coefficient.

I. INTRODUCTION

In recent years, one of the components in the manufacture of optical glass that has been paid much attention by various research groups is chalcogenide [1]. Chalcogenide glasses are based on chalcogen elements (sulfur, selenium, and thorium). This glass is formed by adding other elements such as germanium, gallium, and arsenic [2]. These glasses have unique properties such as high transparency in the infrared region and high nonlinearity compared with other glasses [3].

Chalcogenide glasses depending on their combinations have nonlinear coefficients about 100 to 1000 times greater than that of silica glass. The large refractive index of chalcogenide glasses between 2.4 and 3.0, compared to the other glasses cause to achieve compact nonlinear devices [4, 5]. Due to these properties, chalcogenide glasses are used in the manufacturing of microstructured fibers (MOFs). In MOFs a lattice of air holes as cladding is drawn around the core with high refractive index.

In MOFs light propagation is based upon the total internal reflection (TIR). Two important properties of MOFs are the flexibility in constructing endlessly single mode behavior in light propagations [4]. MOFs are used for technological applications such as telecommunications, medical diagnosis and medical treatments [6]. In telecommunications applications, such as signal regeneration and super-continuum generation require high nonlinearity [7].

Due to the high transparency and low losses of these compounds in the infrared wavelength range, these glasses are used in manufacturing fiber optics used in medical sensing, for the use of, for example, measurements of patient's breathing rhythm when in the presence of strong magnetic fields such as MRI [6]. In order to enhance the nonlinear optical properties of optical fibers, one can use cores with small diameters. MOFs enable us to have a high degree of freedom in designing their geometric structures.

Thus, these structures are suitable for manufacturing fibers with small cores [8, 9]. These fibers can be produced with solid cores and a lattice of hexagonal rings of air holes in the cladding [4]. In order to confine light inside the MOF core, a large contrast between the refractive index of core and cladding is required. A large refractive index difference between the core and the cladding creates two main advantages for MOFs. These two advantages are:

1- In such MOFs, managing optical characteristics such as dispersion is simpler than the conventional fibers and

2- Due to a strong confinement of light in the core, nonlinearity increases [10].

One characteristic, which is important in MOFs, is the flat dispersion in a wide range of wavelengths. To design an MOF with flattened dispersion, high nonlinearity in the infrared wavelength range, low confinement loss and high effective area must be achieved. Many schemes have been used to realize structures with a flat dispersion. Some of the proposed structures include hybrid MOF and multi-ring MOF with different sizes of air holes in cladding or using other materials such as Tellurite in the cladding [10, 11].

By changing the dimension of the geometry, the diameter of the air holes and the distance between the centers of air holes (pitch), one can control the optical properties such as dispersion, confinement loss and the nonlinearity [4]. Therefore, one should choose the geometrical structure, the diameter of the air holes and the distance between the centers of air holes in such a way in order to create a balance between the optical properties mentioned above.

To confine guided light in MOFs in the core area, diameters of the holes in the lattice of cladding need not to be identical. For optimized dispersion, nonlinearity and losses, one can design structures having air holes with different diameters around the core [12]. For flattened dispersion, small air holes needed near the core and for low losses, larger air holes needed further away from the core area [13-15].

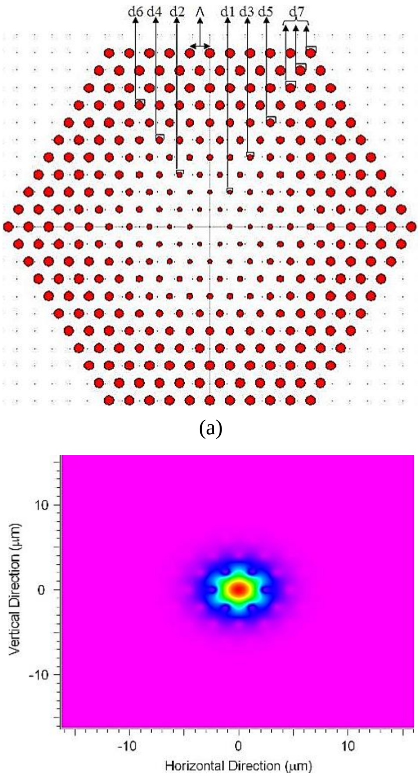
Subsequently, to achieve a structure with flattened dispersion at wide range of wavelengths and low confinement loss, a lattice of air holes with different diameters in the cladding is used. In this paper, we have proposed a new structure with a hexagonal lattice having 10 rings with increasing hole diameters going outwards. Small holes needed near the core to control dispersion and larger holes needed further away from the core to decrease the confinement loss.

II. THE PROPOSED MC-MOF STRUCTURE

In designing MOFs, a couple of points should be taken into considerations. Firstly, the diameter of the air holes by which the dispersion can be managed and secondly, the number of air holes through which the confinement loss can be controlled. However, it is not necessary to have air holes with equal diameters. Subsequently, in the proposed structure for obtaining suitable optical characteristics, air holes with different diameters in ten hexagonal rings are employed in the cladding. For our design purposes, the proposed structure in [12] is used.

Figure 1(a) illustrates the cross-section of the proposed structure. Cladding structure is composed of circular air holes, which are arranged in a 10 ring hexagonal array. In Figure 1(a), distance between the centers of the air holes (pitch) and the air holes diameters, which are located in cladding, are shown with Λ, d_i, respectively, (where, i is the ring number with values i = 1, 2, …,7). This structure has a hexagonal lattice having 10 rings with increasing hole diameters going outwards.

The diameters of the air holes in the three outer rings of the cladding are equal, and this is shown with d_7. The diameters of the air holes in the two inner rings are equal and this is shown with d_1. The pitch is the same throughout the lattice structure. The proposed structure enable us to control nonlinearity, chromatic dispersion and confinement loss more effectively and much easier. Inner rings have a greater impact on dispersion, while the outer rings have greater impact on the confinement losses. The core of MC-MOF is As_2Se_3 chalcogenide glass. Figure 1(b) shows electric field distribution of the fundamental mode at wavelength of 8 μm.



(a)

(b)

Figure 1. (a) Schematic of the proposed MC-MOF, (b) Mode field intensity in the proposed MC-MOF at the wavelength of 8 μm

III. THEORETICAL DISCUSSION

In this section, the numerical method known as plane wave expansion (PWE) that is used in our simulations is described. In addition, we have reviewed optical characteristics, such as dispersion, nonlinearity, confinement loss and effective area.

A. Numerical Method

For the analysis of optical characteristic and determination of light propagation in MOFs, several numerical methods such as finite element method (FEM), scalar effective index method (SEIM), fully vectorial effective index method (FVEIM), plane wave expansion method (PWEM), multi-pole method (MPM) and finite difference time domain method (FDTDM) are available. In all the above methods, the effective refractive index of the cladding is used. The effective refractive index is dependent upon the geometric dimension such as the diameter of the air holes and distance (Λ) between them. In MOFs with various values of d and Λ, different optical properties can be achieved [4].

In this paper, plane wave expansion (PWE) method is used for our design purposes. Plane wave expansion method is a technique for solving the Maxwell's equations in electromagnetics. This method is employed for frequency band and dispersion calculations in MOFs. It is also useful in computing modal solutions of Maxwell's equations in symmetric and non-symmetric structures [16, 17].

B. Dispersion

Widening the pulse propagation in optical fiber is called dispersion. Dependence of the Propagation constant and the effective refractive index to the wavelength causes chromatic dispersion in the fiber. Effective refractive index is calculated with following equation [18]:

$$n_{eff} = \beta \frac{\lambda}{2\pi} \tag{1}$$

where, β is the propagation constant and λ is the wavelength. The total dispersion of the MC-MOF, which is composed of two items, namely, waveguide and material dispersions, is calculated in unit of ps/nm/km using equation below [19]:

$$D(\lambda) = -\frac{\lambda}{c} \times \frac{d^2 \operatorname{Re}\left[n_{eff}\right]}{d\lambda^2} \tag{2}$$

where, Re[n_{eff}] is the real part of effective refractive index and C is the velocity of light in vacuum.

There are several ways to control dispersion in the MOFs. There is a simple method that has been used in our proposal, use of air holes with different diameters d and same Λ in the cladding. Having a low and flat dispersion is very important in MOFs. Flat dispersion in the fiber can be employed in super-continuum generation. The super-continuum generation are used in many applications such as coherence tomography, fluorescence microscopy, flow cytometry.

Major factor in telecommunication systems that limits data bit rates, is the dispersion when propagate within the optical fiber. The simplest technique to compensate dispersion is to employ fibers with high negative dispersion [20]. These fibers are known as dispersion compensating fibers (DCFs). The way it works is that DCF is connected to the end of the telecommunication fiber. Based on Equation (3), for the higher negative dispersion, the smaller length of DCF is needed [21].

$$D_T = D_f \times L_f + D_{DCF} \times L_{DCF} \tag{3}$$

where, D_f and L_f are dispersion and length of telecommunication fiber respectively, while D_{DCF} and L_{DCF} are dispersion and length of DCF. MOFs based on chalcogenide glasses with high negative dispersion features used as DCFs at λ = 1.55 μm [4].

C. Confinement Loss

Light leaking out from core into cladding region is known as the confinement loss. With increasing the number of rings of the air holes around the core of the MC-MOF and also with air holes having greater diameters in the outer ring of cladding, losses can be reduced drastically. The confinement loss L_c, in unit of dB/m., is calculated from the following equation [13]:

$$L_c = \frac{20}{\ln 10} \times \frac{2\pi}{\lambda} \operatorname{Im}(n_{eff}) \tag{4}$$

where, Im(n_{eff}) is the imaginary part of effective refractive index.

D. Effective Area

Another important characteristic of an MC-MOF is effective area. Effective area in unit of μm^2, is calculated as [13]:

$$A_{eff} = \frac{\left(\iint |E|^2\, dxdy\right)^2}{\iint |E|^4\, dxdy} \tag{5}$$

where, |E| is the electric field distribution. Effective area can be increased by enlarging the pitch, while keeping the diameter of air holes constant. MOFs with large effective area are used for transmission of light waves with high powers.

E. Nonlinear Coefficient

Nonlinearity becomes important, when light with high intensity is coupled with the core of proposed MC-MOF. Effective area has an inverse relationship with nonlinearity. MC-MOF with small core can have high nonlinearity. Nonlinear coefficient in unit of W^{-1}m^{-1} is calculated as [13]:

$$\gamma = \left(\frac{2\pi}{\lambda}\right)\left(\frac{n_2}{A_{eff}}\right) \tag{6}$$

where, n_2 is the nonlinear index, which for As_2Se_3 chalcogenide glass is 2.4×10^{-17} m^2/W, and for air is 2.9×10^{-23} m^2/W [7].

Small diameter core increases the nonlinear characteristic of MOFs. However, a small core, also limits the power transfer. Solution this limitation, is core with high nonlinearity such as chalcogenide glasses. According to the above discussions, for managing optical characteristics in MOFs, changing the values of d and Λ are needed. On the other hand, the condition of single-mode behavior in MOFs occurs when $d / \Lambda \le 0.45$. So to create a balance between the optical characteristics, defects should be created in the shape and the ordering of the air holes [4].

IV. SIMULATION RESULTS

We have calculated dispersion in our MC-MOF structure for several values of the pitch and diameter of air holes. Initially, we started our simulations with *pitch* = 2.3 μm and the hole diameters in μm which is expressed by the relationship $d_{i+1} = d_1 + (i \times 0.1)$, where $i = 0, 1, \ldots, 6$.

Figure 2 shows dispersion curves versus wavelength, for different hole diameters, d_1 = 0.3, 0.4, 0.5 μm. Considering the dispersion curve shown in Figure 2, the structure with smaller air holes (d_1 = 0.3 μm) at the wavelength range of 8.5 to 18 μm has flattened dispersion with a corresponding value of -5 ps/nm/km. Our result is greatly improved, when compared with the dispersion results from [10], which have dispersion value between ±25 ps/nm/km at the wavelength range of 2.5 to 10 μm.

We have also compared our results with those of [11], which have dispersion values between -25 and 32 ps/nm/km from 1.5 to 3.8 μm wavelength range. By increasing the diameter of the air holes in our structure, as shown in Figure 2, both values of dispersion and slope of dispersion curve over wavelength range from 8.5 to 18 μm increase. To examine effect of pitch on dispersion, simulations are done with $d_{i+1} = 0.3 + (i \times 0.1)$ μm and Λ = 1.5, 2.3, 3 μm. Results are shown in Figure 3.

According to this Figure 3, we can conclude that by reducing the pitch, the wavelength range over which the dispersion is flat, reduces. This is confirmed in [4]. Changing the diameters of the air holes that are far from the core has negligible effects on dispersion. This case is discussed in [12]. Figure 4 shows our simulation results of dispersion versus wavelength for Λ = 3 μm, d_6 = 0.45 μm and d_7 = 0.7 μm. It is clear from this figure, that the changes in air hole diameters in the 4 outer rings have no effect on dispersion. Another optical feature in proposed MC-MOF that has been studied is the effective area.

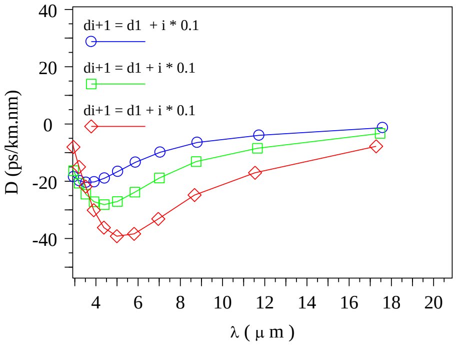


Figure 2. Dispersion curve with Λ = 2.3 μm and d_1 = 0.3, 0.4, 0.5 μm

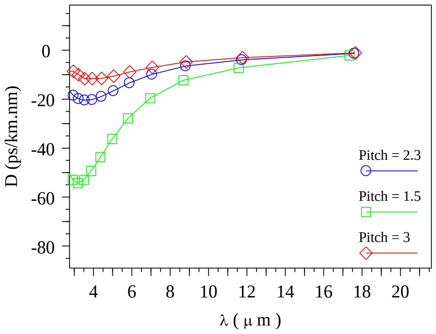


Figure 3. Dispersion curves for $d_{i+1} = 0.3 + (i \times 0.1)$ μm, Λ = 1.5, 2.3, 3 μm

Figure 5 shows the effective area versus wavelength for Λ = 1.5, 2.3, 3 μm with $d_{i+1} = 0.3 + (i \times 0.1)$ μm. It can be observed that by increasing Λ, the effective area is increased. For example, effective area with *pitch* = 3 μm is 7.2 μm^2. In [4] it has been shown that increasing the pitch, effective area is increased, which in turn, confirms our results. Nonlinear coefficient (γ) which is important for nonlinear effects (four wave mixing, stimulated Raman and Brillion scattering) is also examined.

Figure 6 shows nonlinear coefficient versus wavelength for proposed MC-MOF. As shown in Figure 6, nonlinear coefficient for λ = 8 μm is 1.2 W^{-1}m^{-1} but, nonlinear coefficient for λ = 8 μm in multi-ring structure in [10] is 0.20952 W^{-1}m^{-1}. This confirms that our structure behaves better. As a result, our structure is suitable for broadband optical amplification, wavelength conversion, and super-continuum generation in mid-infrared region. The confinement loss is next feature of the structure that is studied here. Confinement loss versus wavelength in proposed MC-MOF, for Λ=3 μm and $d_{i+1}=0.3+(i \times 0.1)$ μm is shown in Figure 7. According to Figure 7, confinement loss in our structure at the wavelength range less than 13 μm, is around zero.

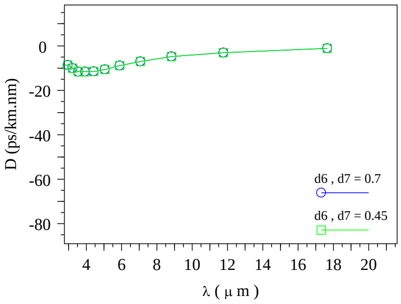


Figure 4. Dispersion curve for Λ = 3 μm and d_6, d_7 = 0.45. 0.7 μm

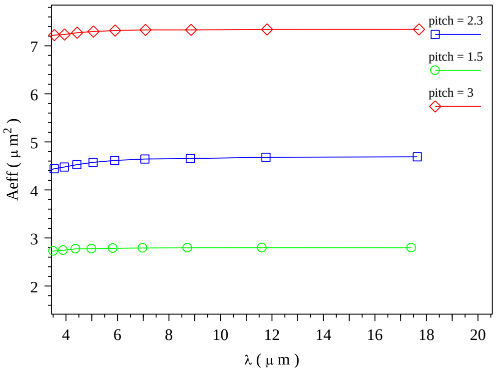


Figure 5. Effective area for Λ = 1.5, 2.3, 3 μm

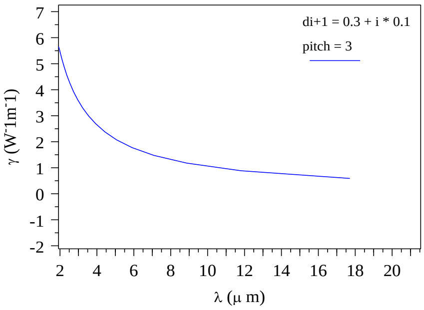


Figure 6. Nonlinear coefficient versus wavelength for Λ = 3 μm

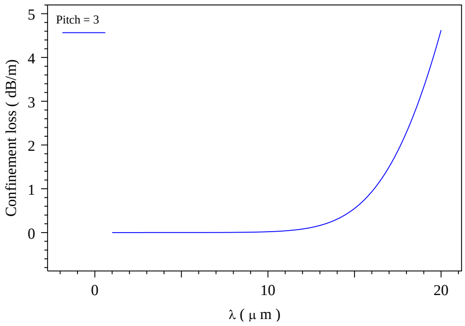


Figure 7. Confinement loss versus wavelength

The most important reason for low confinement loss in our structure is the large number of air holes. Dispersion at λ = 1.55 μm is very important for communication applications. The proposed structure in this paper, for Λ = 3 μm and have dispersion value of 5 ps/nm/km at λ = 1.55 μm. Figure 8 shows dispersion in communication window. Figure 9 shows the refractive index of MC-MOF for *pitch* = 1.5, 2.3 μm. For *pitch* = 2.3 μm at 8.5 to 18 μm range, refractive index is approximately is constant.

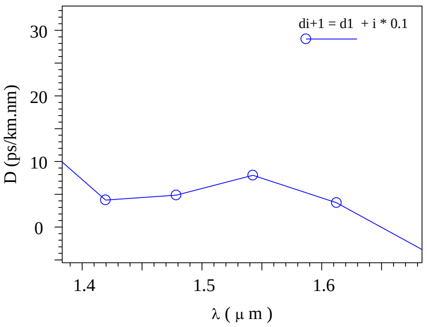


Figure 8. Dispersion in communication window

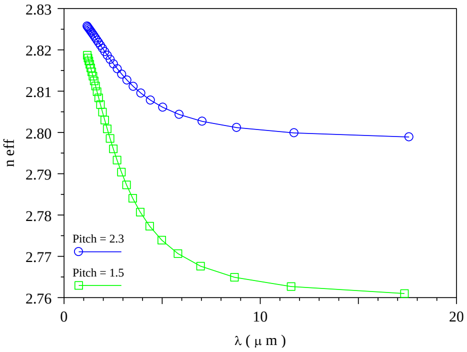


Figure 9. Refractive index versus wavelength

V. CONCLUSIONS

In this paper, a new design of As_2Se_3 chalcogenide glass multi cladding MOF (MC-MOF) has been proposed. In MC-MOF with air holes of different diameters, a balance in optical characteristics is created. We have demonstrated that this structure has a low dispersion of about 5 ps/nm/km at λ = 1.55 µm that can be used in communications systems and also it has a flat dispersion with a value of -5 ps/nm/km at the wavelength range of 8.5 to 18 µm. This paper also illustrated that dimensions of the structure affect the dispersion features.

Therefore, by increasing the pitch, the wavelength range with flat dispersion, increases. It is also shown that, air holes in the outer ring have no effect on dispersion characteristic. Our results show that effective area increases with increasing the distance between the air holes. Confinement loss of this MC-MOF structure is low, (around zero), at the wavelength range less than 13µm. The nonlinearity coefficient γ at the 11 to 18 µm wavelength range is as high as 1 $W^{-1}m^{-1}$, thus making this structure suitable for broadband optical amplification, wavelength conversion, and supercontinuum generation in mid-infrared region.

NOMENCLATURES

MOFs: Micro-structured Optical Fiber
MC-MOF: Multi Cladding Micro-structured Optical Fiber
FEM: Finite Element Method
SEIM: Scalar Effective Index Method
FVEIM: Fully Vectorial Effective Index Method
PWEM: Plane Wave Expansion Method
MPM: Multi-Pole Method
FDTDM: Finite Difference Time Domain Method
DCFs: Dispersion Compensating Fibers
Λ: Distance between the centers of air holes
d: Air hole diameter
d_i: Air hole diameter in the ith ring
β: is the propagation constant
λ: is the wavelength
$D(\lambda)$: Dispersion
γ: Nonlinear coefficient
$\mathrm{Re}[n_{eff}]$: Real part of effective refractive index
$\mathrm{Im}(n_{eff})$: Imaginary part of effective refractive index
L_c: Confinement loss
A_{eff}: Effective area
n_2: Nonlinear index
D_f: Dispersion fiber transmission
L_f: Length of fiber transmission
D_{DCF}: Dispersion of DCF
L_{DCF}: Length of DCF

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BIOGRAPHIES

Mahmood Seifouri received the B.Sc. and Ph.D. degrees in Electrical and Electronic Engineering from the University of Wales College of Cardiff, UK, in 1985 and 1989, respectively. After spending two years as a Lecturer at Brighton University, UK, he moved to Iran University of Science and Technology, Tehran, Iran in 1991. After spending 9 years at the mentioned university, in 2000, he was employed as a Senior Development Engineer at Bookham Technology, UK, where he was primarily involved in research and development projects in the field of optoelectronics. In September 2001, he joined Optometrics, CA, USA, as a Senior Development Engineer and continued with his work over there. Since 2006, he has been with the Faculty of Electrical and Computer Engineering, Shahid Rajaee Teacher Training University, Tehran, Iran. His research interests include experimental and numerical studies of electromagnetic fields and waves with particular emphasis on the theory, modeling and simulation of optical waveguides, lasers, amplifiers and nano-scale photonic circuits.

Saeed Olyaee was born in Mashhad, Iran, on 31 December 1974. He received the B.Sc. degree in Electrical Engineering from University of Mazandaran, Babol, Iran, in 1997 and the M.Sc. and Ph.D. degrees in Electrical Engineering Specializing in Optoelectronics from Iran University of Science and Technology, Tehran, Iran, in 1999 and 2007, respectively. His doctoral dissertation concerned nanometric displacement measurement based on three-longitudinal-mode laser. He has established the Nano-photonics and Optoelectronics Research Laboratory, NORLab, in 2006 and currently, he is the head of NORLab and Vice-President for Research and Technology in Shahid Rajaee Teacher Training University, Tehran, Iran. He presented and published more than 120 scientific conference and journal papers, book, and book chapters, and currently he is Responsible Director of Journal of Electrical and Computer Engineering Innovations (JECEI) and Member of Scientific Committee of several National and International Conferences. His main research interests include laser displacement measurement, nano-metrology, optical instrumentation and photonic crystal fibers.

Moslem Dekamin was born in Nahavand, Iran, in 1984. He received the B.Sc. and M.Sc. degrees in Electrical Engineering from Shahid Rajaee Teacher Training University, Tehran, Iran in 2006 and 2013, respectively. His research interest include microstructured optical fiber.